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HIGH POWER MILLIMETER WAVE AMPLIFIER

Varian Associates

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HIGH POWER MILLIMETER WAVE AMPLIFIER

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Gyro-TWT	Cyclotron Harmonic Operation
Microwave Tube	Millimeter Wave Amplifier
C-band Oscillations	

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This interim report describes the measured performance of a three cavity Gyroklystron amplifier designed to operate at X-band with the signal frequency near the second harmonic of the Cyclotron frequency. Efficiency and gain were measured as a function of various operating parameters. Performance of the experimental device was significantly limited by the need to avoid spurious oscillations. The maximum gain was 10 dB and the maximum efficiency was 8 percent. Noise figure and spectrum measurements yielded values similar to high-power linear beam tubes. (over)

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Design considerations for converting the experimental Gyroklystron to a Gyro-TWT are discussed. A Gyro-TWT using the TE_{11} cylindrical mode with operation at the fundamental Cyclotron frequency was found to be compatible with existing hardware. Considerations for a second experiment using the TE_{01} cylindrical mode and the second Cyclotron harmonic are also discussed.

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1. INTRODUCTION

This program has the objective to develop a high power pulsed amplifier for millimeter wave operation. Desired operating characteristics are:

center frequency	94 GHz
electronic bandwidth	> 4%
peak power	100 kW
average power	10 kW
beam efficiency	30%
power gain	30 dB.

The development is limited to the consideration of gyrotron-type amplifiers which involve an interaction based on cyclotron resonance. Operation with magnets at room temperature is desired rather than superconducting magnets. This implies operation at harmonics of the cyclotron frequency.

The present program was preceded by a Phase I study effort [(1)] which explored the feasibility of gyroklystron amplifiers with cyclotron harmonic operation. As part of the study effort, a three-cavity gyroklystron amplifier operating on the second harmonic of the cyclotron frequency at X-band was built and partially tested.

This interim report covers the completion of testing of the X-band gyroklystron built under the previous study program. Measurements of saturated output power are included in the report. Spectrum measurements and noise figure measurements are also presented.

The report includes a discussion of the alternative considered to convert the existing experimental device for tests as a gyro-TWT amplifier. The best course of action appears to be testing of a gyro-TWT operating at the fundamental cyclotron resonance at C-band, followed by operation at the second cyclotron harmonic at X-band.

II. REVIEW OF THE PHASE I AMPLIFIER

The amplifier which was constructed in Phase I is a three-cavity gyroklystron, for operation at 10.35 GHz. It was designed to operate at the second harmonic of the cyclotron resonance condition. The resonance condition is given by the equation

$$\omega = \frac{neB}{\gamma m_o} \tag{1}$$

where ω is the operating frequency, B is the axial dc magnetic field, e/m_o is the charge-to-mass ratio of the electron, γ is the relativistic mass factor, and n is the harmonic number. Operation at the second harmonic of the resonance allows the magnetic field to be smaller by a factor of two. The fundamental cyclotron resonance at 94 GHz requires a magnetic field of about 33 kg and second harmonic operation requires 16.5 kg. Hence the magnitude of field required is high enough to make operation at second or third harmonic worth considering.

The operating parameters for the 10.35 GHz amplifier are given in Table 1. Additional information on the design is included in the final report for Phase 1 (1).

Initial operation resulted in the observation of a microwave gain of 9 to 10 dB under small signal conditions where the power output was about 100 W peak. This operation was achieved at reduced beam voltage of 40 kV. Amplifier operation at higher beam voltage had been prevented by interfering oscillations involving the TE_{111} resonance in the input cavity interacting with the fundamental cyclotron resonance condition. The oscillation occurred at a frequency near 5.4 GHz and was somewhat tunable depending on main magnetic field values. Table 2 shows a summary of preliminary test values compared to design values.

TABLE 1
10.35 GHz AMPLIFIER DESIGN VALUES

1.	Power output - peak	100	kw
	average	5	kW
2.	Gain	30	dB
3.	Bandwidth	0.1	%
4.	Magnetic field	1.96	kg
5.	RF circuits (TE_{011} cavities)		
	Input cavity length	1.5	λ *
	First drift length	1.2	λ
	Center cavity length	1.5	λ
	Second drift length	1.2	λ
	Output cavity length	3	λ
	Cavity loaded Q (each cavity)	1000	
	Drift tube radius (0.51)	0.58	in
6.	Beam		
	Voltage	60	kV
	Current	5	A
	Outer beam radius	0.53	in
	Inner beam radius	0.19	in
	Axial velocity	0.2	c **
	Transverse velocity	0.4	c
	Electron orbit radius	0.15	in

* λ = Free-space wavelength at the operating frequency.

** c = velocity of light

TABLE 2

SUMMARY OF PRELIMINARY TEST RESULTS

Parameter	Design Value	Preliminary Test Value
Beam Voltage	60 kV	40 kV
Gun anode voltage	31 kV (52%)	24 kV (60%)
Beam current	5 A	4.5 A
Main magnet field	1960 g	1960 g ± 5%
Gun magnet	485 g	450 g ± 10%
Microwave gain	23 - 26 dB	9 - 10 dB
Peak body current	0	80 ma
Peak gun anode current	0	<4 ma

III. HIGH POWER TESTING OF THE PHASE I AMPLIFIER

At the start of Phase II, a linear-beam klystron capable of about 8 kw peak output power was installed as a driver for the gyroklystron, allowing the gyroklystron to be driven to saturation. Figure 1 shows a typical saturated power curve. The 40 kV, 4.0 A beam parameters were the nominal values used in the majority of the measurements performed. Higher values of beam voltage and current yielded marginal operating points and did not allow exploration of the parameter space. However, the highest values of saturated power, small signal gain, and efficiency were obtained at 50 kV and 5.0 A. The data for this result are summarized in Table 3, and the saturated power curve appears in Figure 2.

TABLE 3
BEST PERFORMANCE

Parameters	Test Value
Beam voltage	50 kV
Beam current	5.0 A
Saturated power	20.56 kw
Small signal gain	5.8 dB
Gain compression	1.4 dB
Saturated efficiency	8.2%

Eight independent variables affect the performance of the gyroklystron in test: beam voltage and current, anode voltage, the four sections of the main magnet, and the gun coil current. The first of these, beam voltage, has a limited range (if all others are held fixed) due to the onset of undesired oscillations mentioned in Section II. Figure 3 shows the result of varying the beam voltage from 35 kV to 45 kV. It should be noted that anode voltage is changing also since the

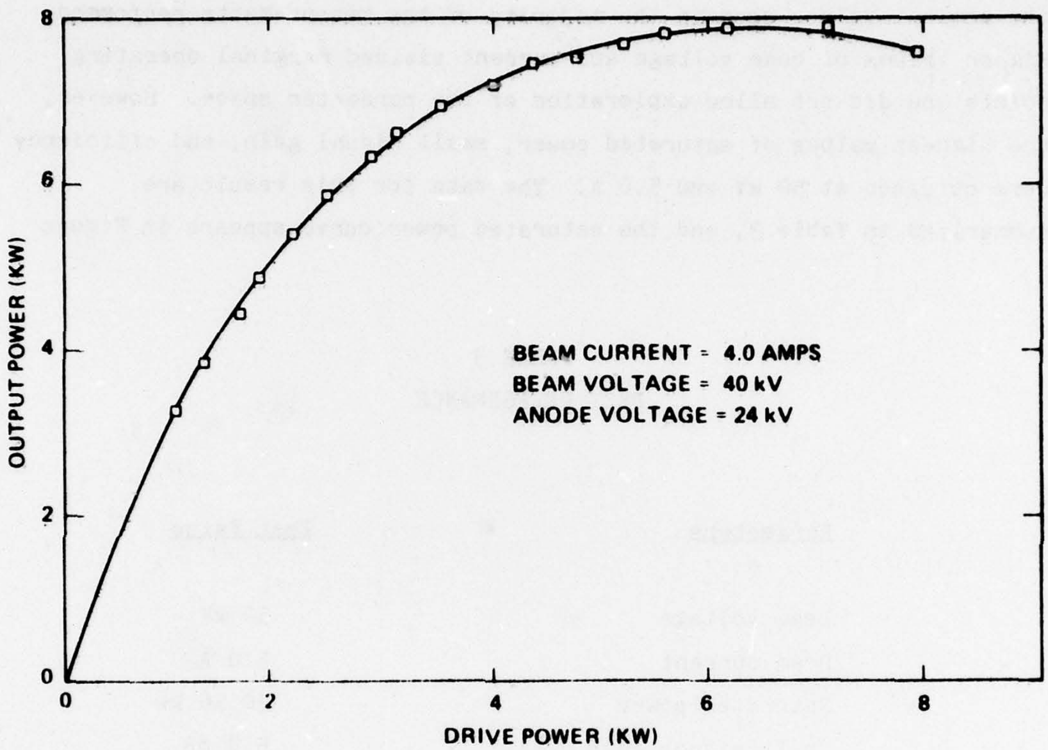

Figure 1. Saturated Output-Gyroklystron

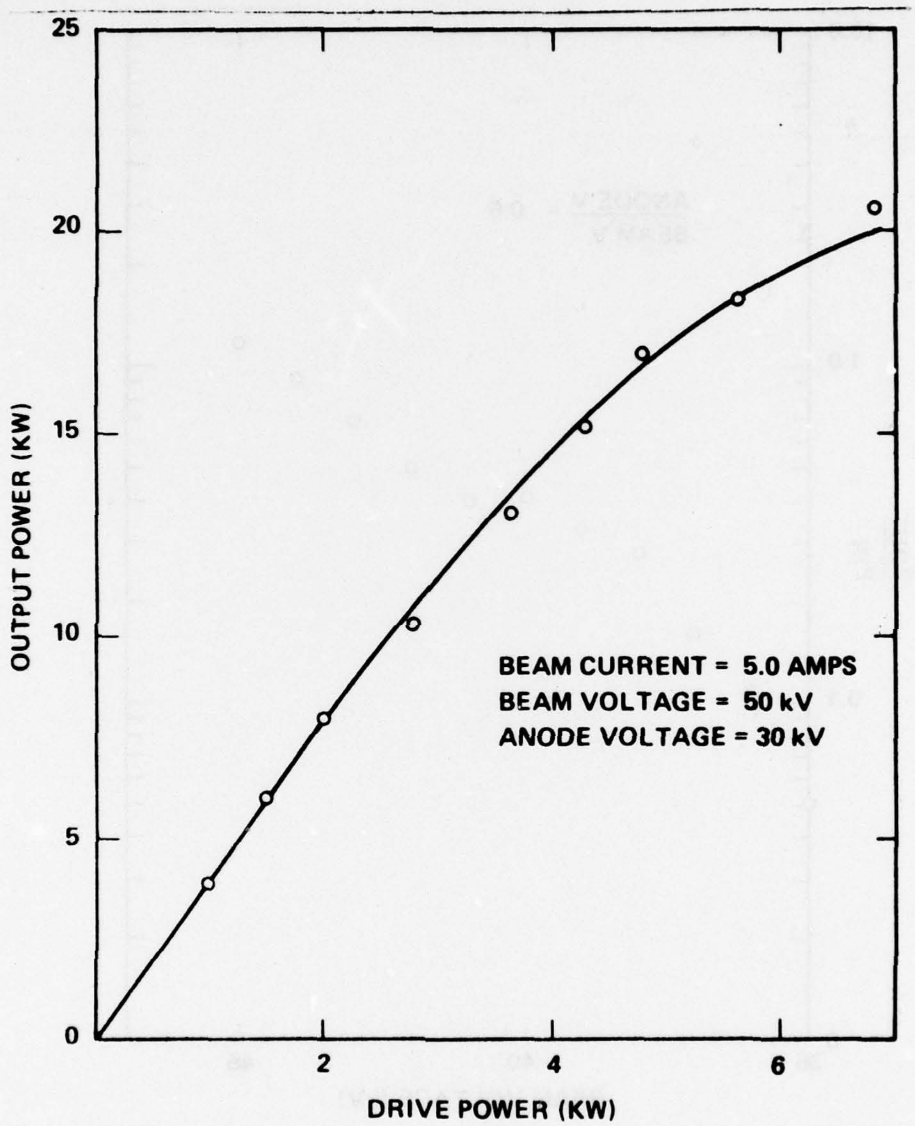

Figure 2. Output Power vs Drive Power – Best Results

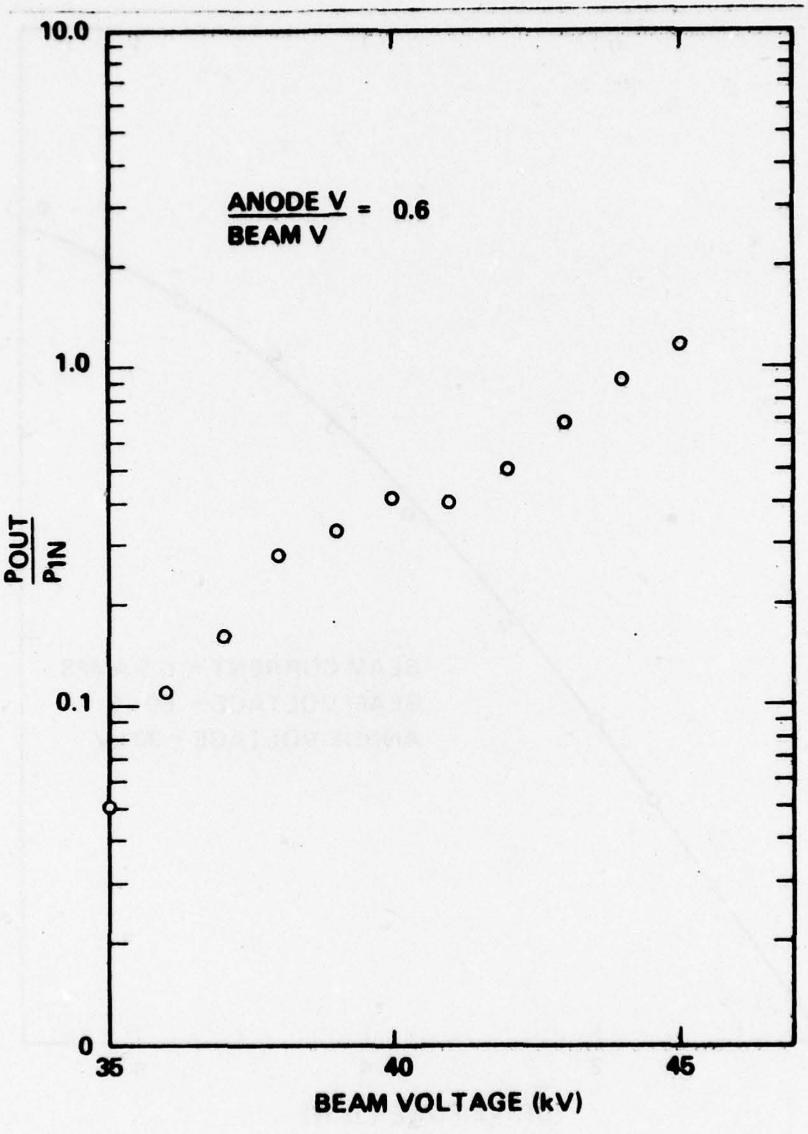

Figure 3. Gain vs Beam Voltage

ratio is fixed. It was impractical to attempt to keep anode voltage fixed, but all magnetic fields were fixed.

The cathode is operated in a temperature-limited mode; hence, the beam current is easily varied by adjusting the heater power. Figure 4 depicts the increase in saturated output power as the beam current is increased. The regions above 5.0 A and below 3.2 A were disturbed by unstable behavior in the gun-anode region.

The magnetic field from the gun coil is the major contributor to flux threading the cathode. The flux determines, along with anode voltage, the amount of transverse energy on the beam. The gain of the gyroklystron should increase as the coil current is reduced; Figure 5 shows this effect. The total dynamic range produced is 11 dB. Lower values of gun coil current were prevented by oscillations.

Figures 6 through 9 show the variation in small-signal output power as the currents in each of the main sections are varied. The three sections closest to the collector exhibited definite maximum points of 3-6 dB. The coil closest to the anode caused a gradual increase in output as the current was raised to the supply's limit.

An investigation of bandwidth, obtained by varying the drive frequency, yielded the curve of Figure 10. The half-power bandwidth is 13 MHz.

Table 4 shows the baseline values used in the experiments which yielded Figures 4 through 10.

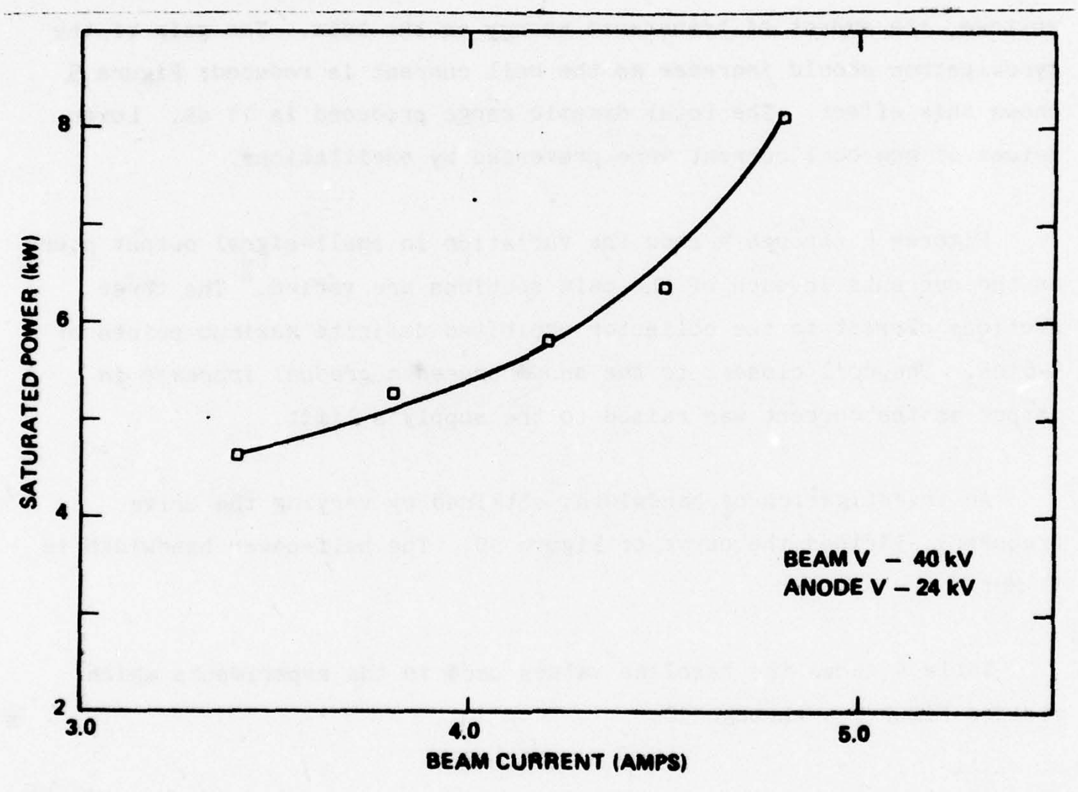

Figure 4. Saturated Power vs Beam Current

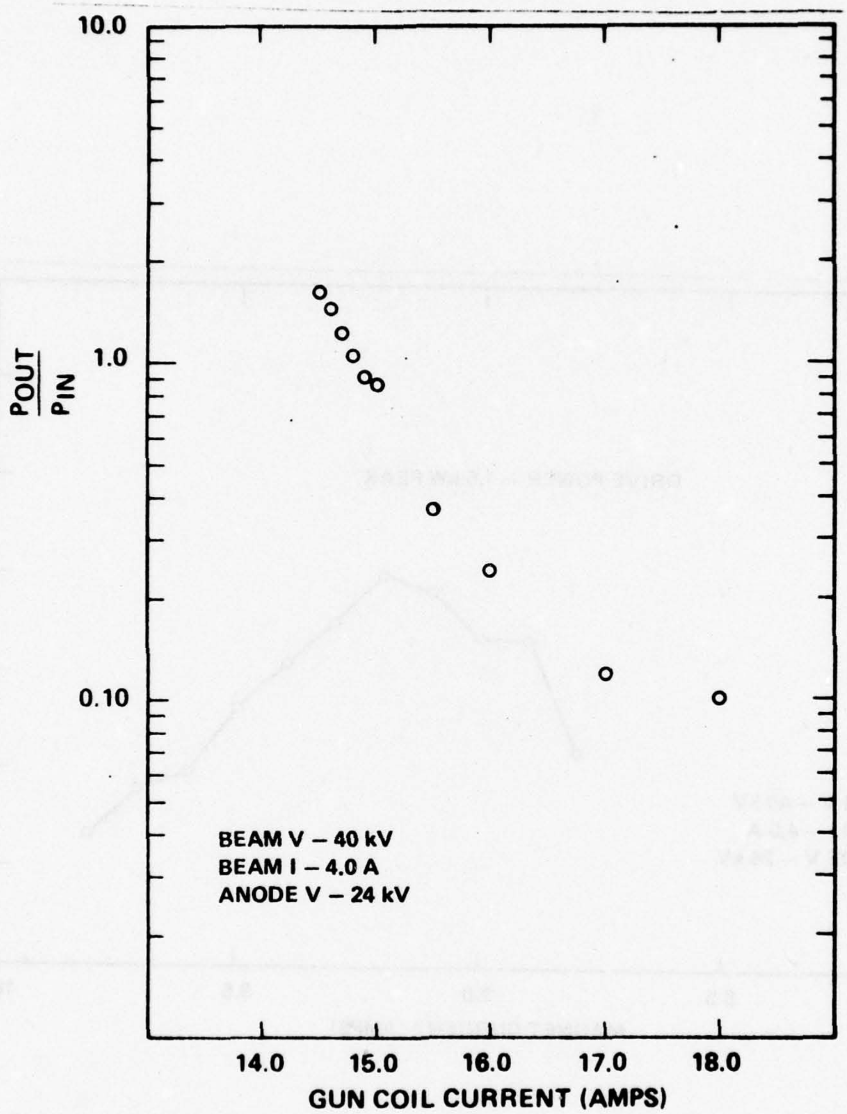

Figure 5. Gain vs Gun Coil Current

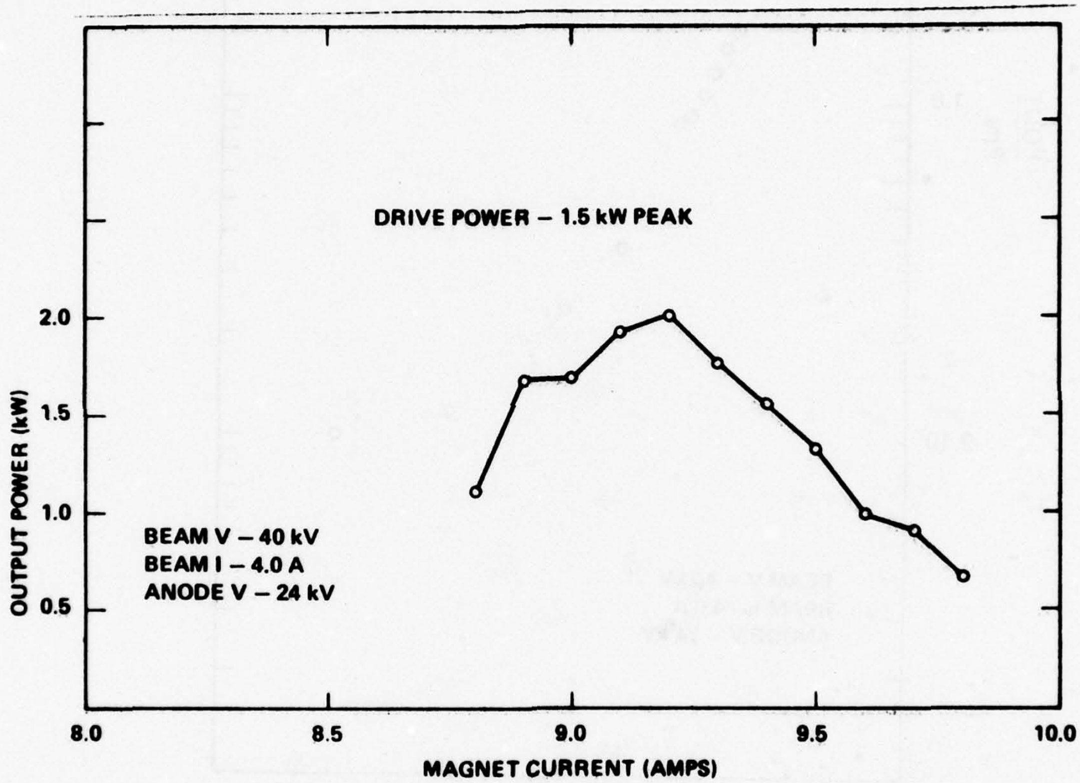

Figure 6. Peak Output Power vs Current – Main No. 1 (Collector End)

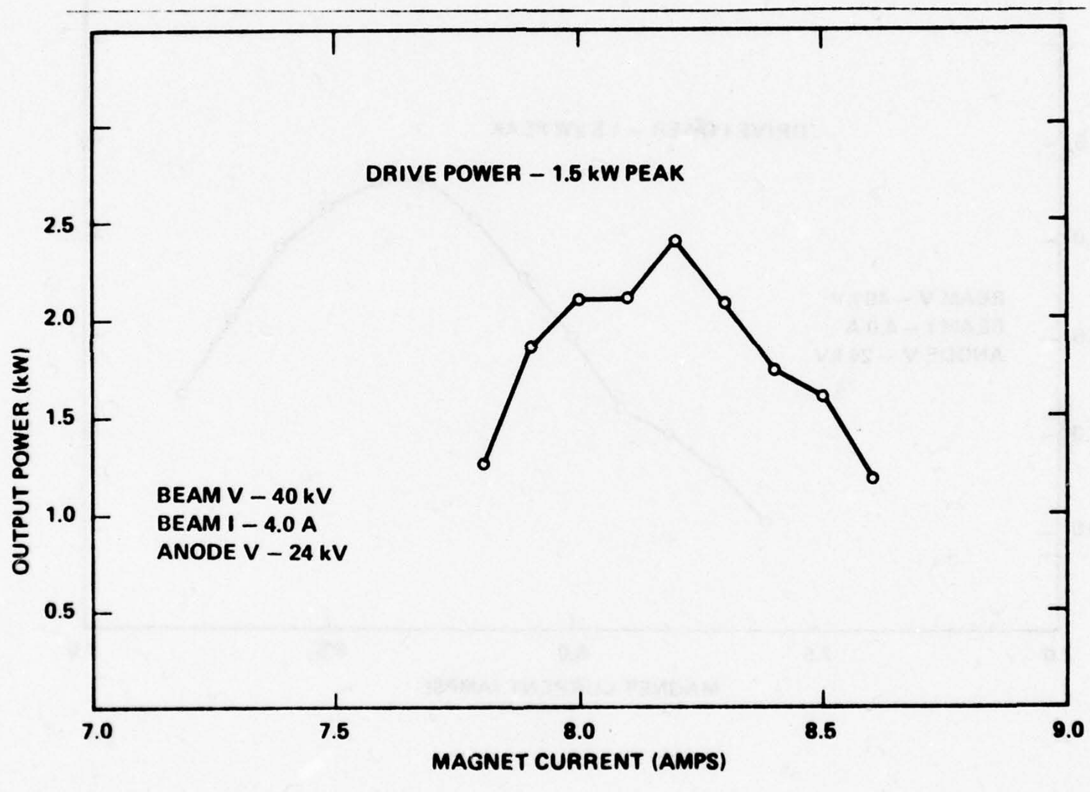

Figure 7. Peak Output Power vs Current – Main No. 2

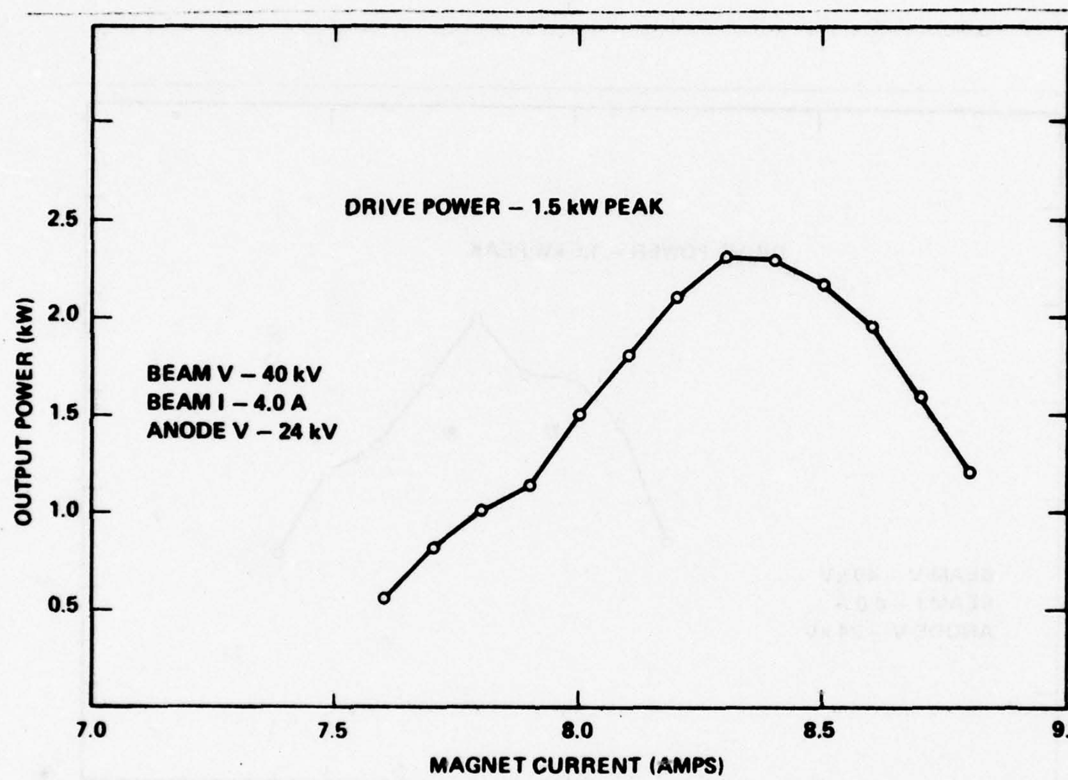

Figure 8. Peak Output Power vs Current – Main No. 3

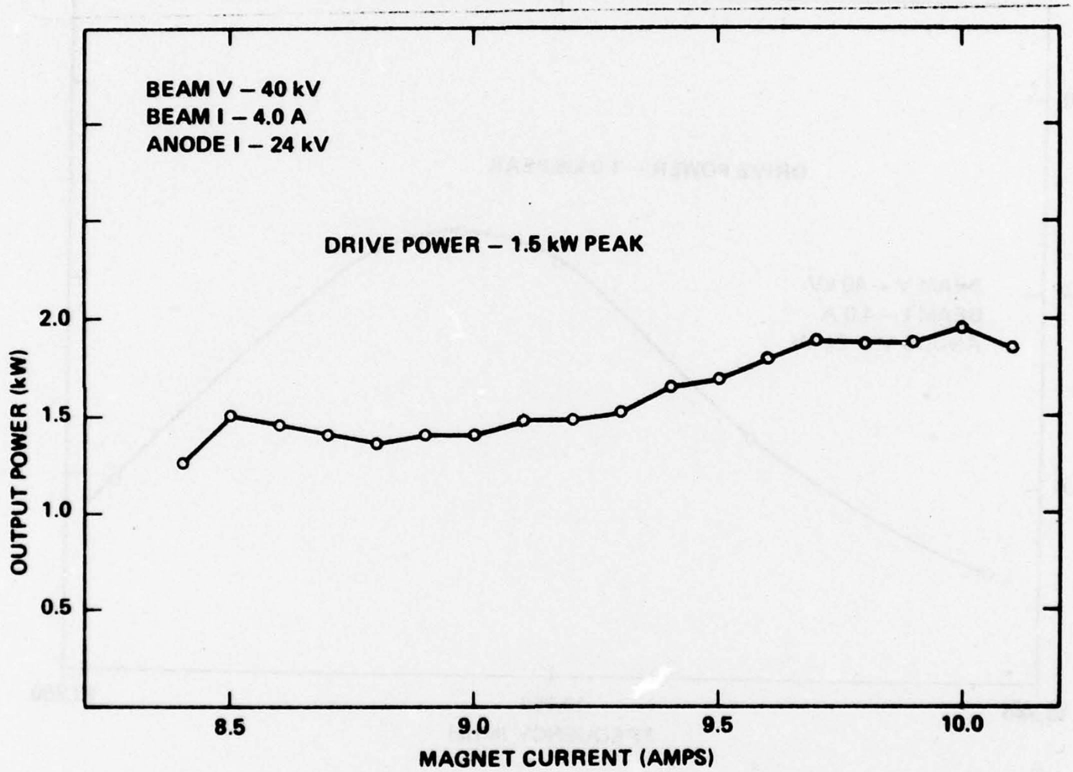

Figure 9. Peak Output Power vs Current – Main No. 4 (Anode End)

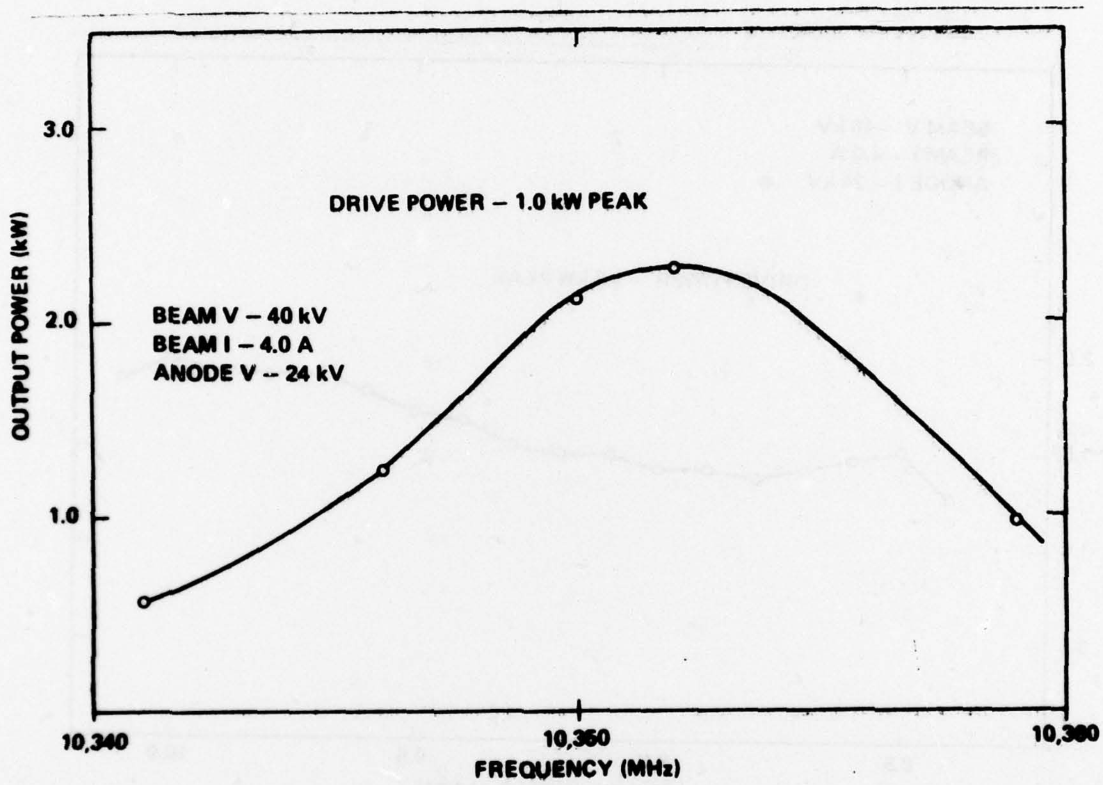

Figure 10. Output Power vs Drive Frequency

TABLE 4
NOMINAL OPERATING PARAMETERS

Beam Voltage	40.0	kV
Beam Current	4.0	A
Anode Voltage	24.0	kV
Magnet Coil Current		A
Main 1	9.3	
2	8.2	
3	8.6	
4	10.0	
Gun	14.5	

Two measurements were made pertaining to the signal quality of the gyroklystron output. The first of these was a determination of a noise figure. The gyroklystron input port was terminated in a matched load. The resulting output was mixed down and sent to an IF amplifier, and then video displayed. The output of a gas discharge tube, with a known noise figure, was gated with a PIN diode modulator and then processed through the mixer and IF amplifier. The two pulses were compared on the display. Table 5 shows the noise figures obtained at different gyrotron operating points.

TABLE 5

NOISE FIGURE*

Operating Point (Small-Signal Gain)	Noise Figure
1 dB	53 dB
6 dB	59 dB

* Noise figures are referenced to thermal noise (Johnson noise), about -204 dBw.

Spectrum analyzer displays of the gyroklystron output were recorded. A reflex klystron oscillator replaced the klystron amplifier as a drive source for the gyrotron. The output of the oscillator was gated with a PIN diode modulator. The combination provided a spectral input to the gyroklystron as shown in Figure 11. Figure 12 shows the resulting output spectrum.

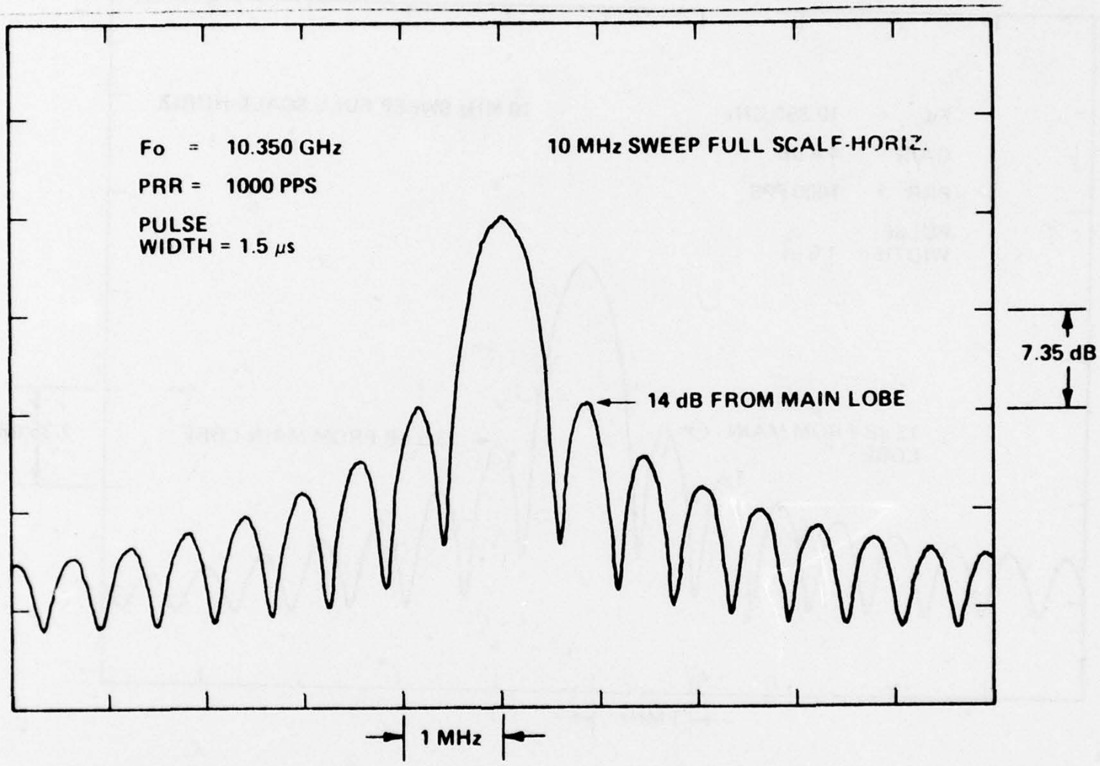

Figure 11. Gyrotron Input (Reflex Klystron) – S/A Log Display

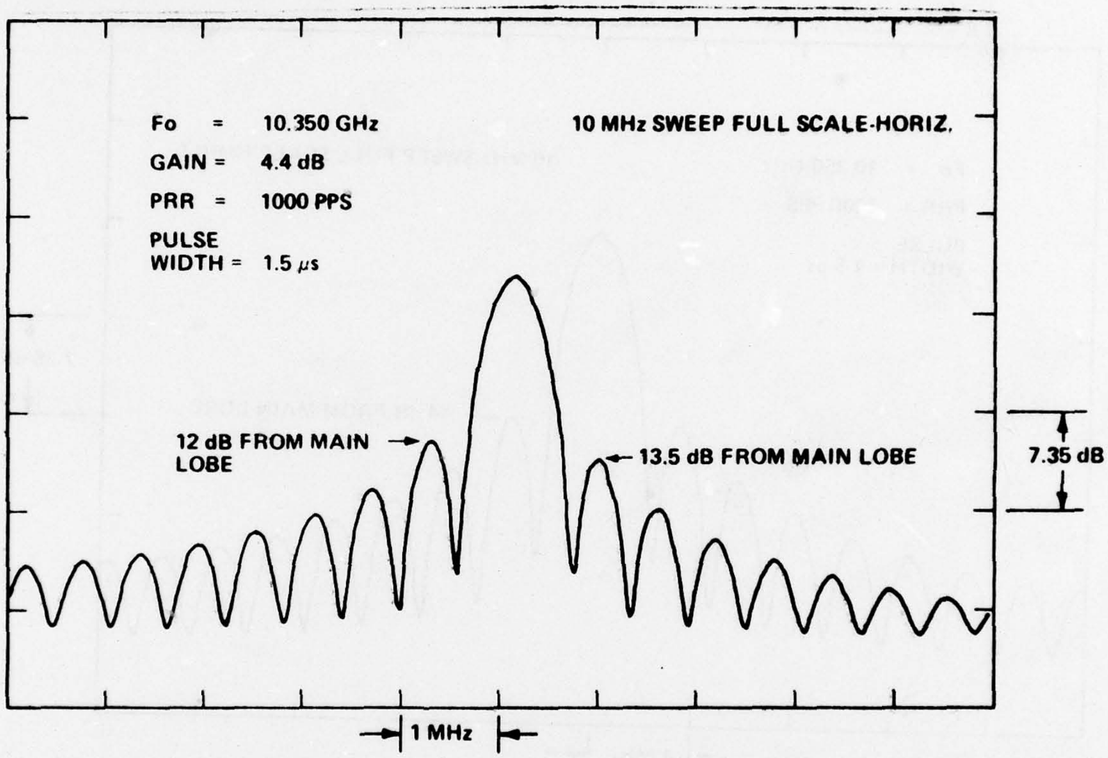

Figure 12. Gyrotron Output – S/A Log Display

IV. DESIGN OF THE GYRO-TWT

The gyro-TWT version of the family of cyclotron resonance masers differs from the klystron or monotron by virtue of its non-resonant rf circuit. The beam is well-coupled to the EM fields over a reasonable bandwidth (5-10%). Unlike a conventional (linear beam) TWT, the gyro-TWT utilizes a fast-wave interaction between circuit and beam. This allows the use of simple, non-periodic rf circuits.

Investigation of a gyro-TWT amplifier was considered highly desirable in view of the limited bandwidth predicted for the gyroklystron in the final report for Phase I [1]. Calculations of efficiency in gyro-TWTs operating at the fundamental cyclotron resonance frequency became available [2,3]. The calculations suggested an efficiency of up to 50% for the fundamental interaction dropping to 11 to 15% for the third harmonic and 6 to 9% for the fourth harmonic.

Because of the sensitivity of efficiency to cyclotron harmonic number and because the higher harmonic interactions are expected to be more difficult to stabilize, it was decided that experiments should be performed involving the fundamental and second harmonic interactions before proceeding to higher harmonics.

To minimize development time and cost it was decided to design gyro-TWT experiments using the gyroklystron hardware from Phase I wherever possible. In particular, the existing solenoid and gun designs were to be used.

At the start of Phase II, efforts were made to develop a scheme for coupling to the traveling wave circuit in a manner that allowed operating with several of the waveguide modes (TE_{11}, TE_{21}, TE_{01}) at different frequencies. This proved to be impractical and it was decided to build a different rf circuit for the fundamental and second harmonic tests, and perform two experiments by substituting the appropriate circuit into the existing vehicle.

One experiment will employ the TE_{11} mode in the circular guide and will operate at the fundamental cyclotron resonance, about 5.2 GHz. (10.35 GHz fundamental operation is beyond the capability of the existing solenoid.) The input coupling system must fit within the magnet bore, which is difficult at 5.2 GHz if conventional rectangular waveguide components are used. An attempt was made to couple to the rf circuit using a coaxial transmission line terminated in a probe or loop. The close proximity of the beam to the wall of the interaction circuit required the use of small loops or probes which had high radiation resistances, and required excessive impedance transformation to achieve an acceptable match. A hybrid solution was found involving coupling to the circuit with a rectangular waveguide port and then using a vacuum tight coax-to-waveguide transition. The matching for the rectangular guide to the interaction circuit required a capacitance at the junction. The result appears in the reflected power plot of Figure 13. A similar plot for the coax-to-waveguide plot is shown in Figure 14. Since two orthogonal TE_{11} modes can exist, two inputs will be required separated 90^{o} azimuthally.

The second experiment will utilize the TE_{01} mode operating at the second harmonic of the cyclotron resonance (10.35 GHz). This circuit may require some mode filtering to suppress the TE_{11} and TE_{21} modes. Some work has been done to couple to the TE_{01} with a rectangular guide.

Figure 15 shows one attempt that used an inductance at the discontinuity. Qualitative tests indicate there is relatively little conversion to non-TE_{01} modes.

For the gyro-TWT experiment, using the TE_{11} mode, a change in the output window design is required. The previous window design had an axial break in the guide wall suitable for the TE_{01} mode and was matched for operation at 10.35 GHz. For use with TE_{11} mode, the axial wall gap will be removed, and the window thickness will be increased for a C-band match.

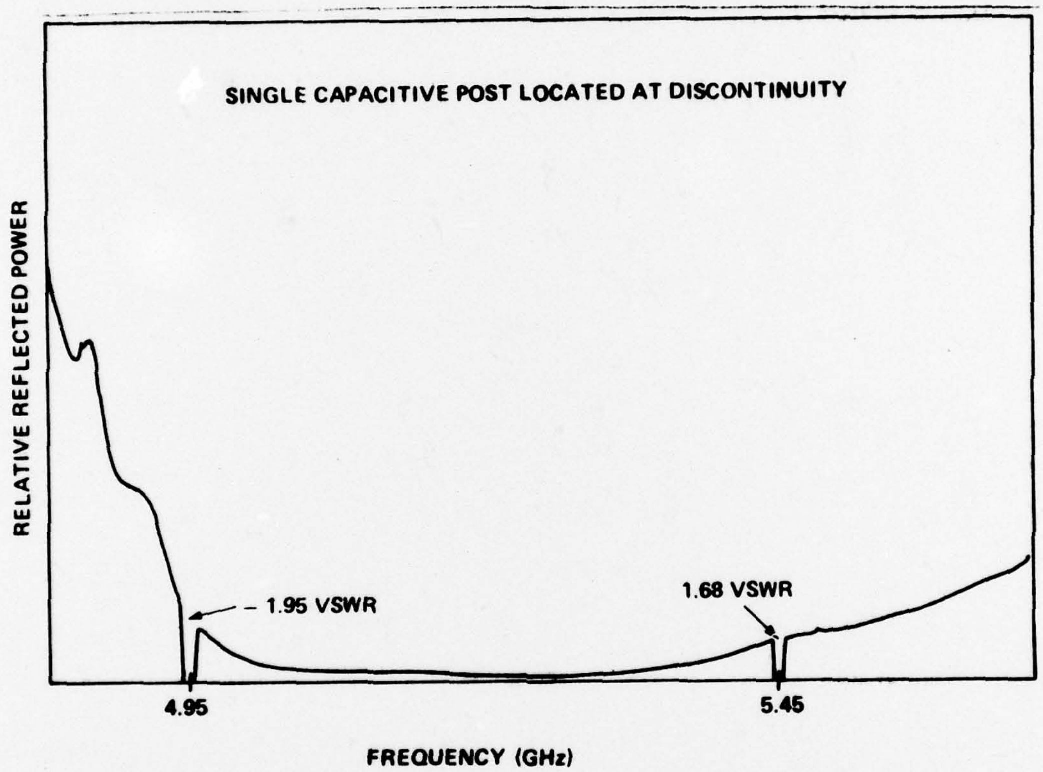

Figure 13. Reflected Power (TE_{11} Circuit)

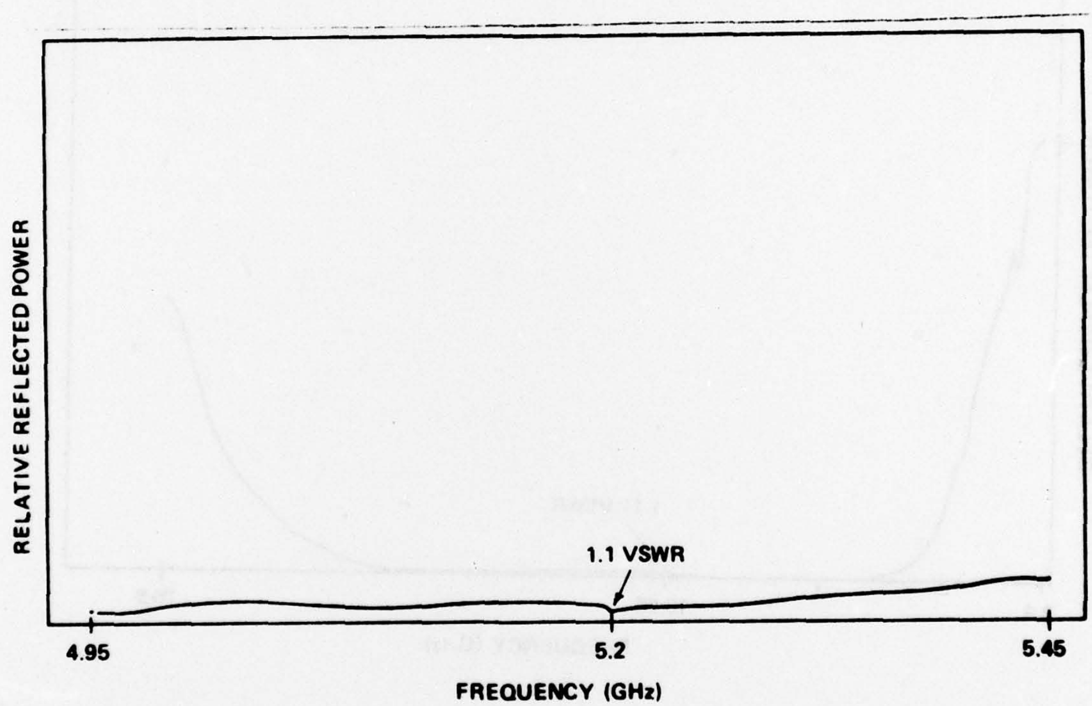

Figure 14. Reflected Power – Coax to Waveguide Transition

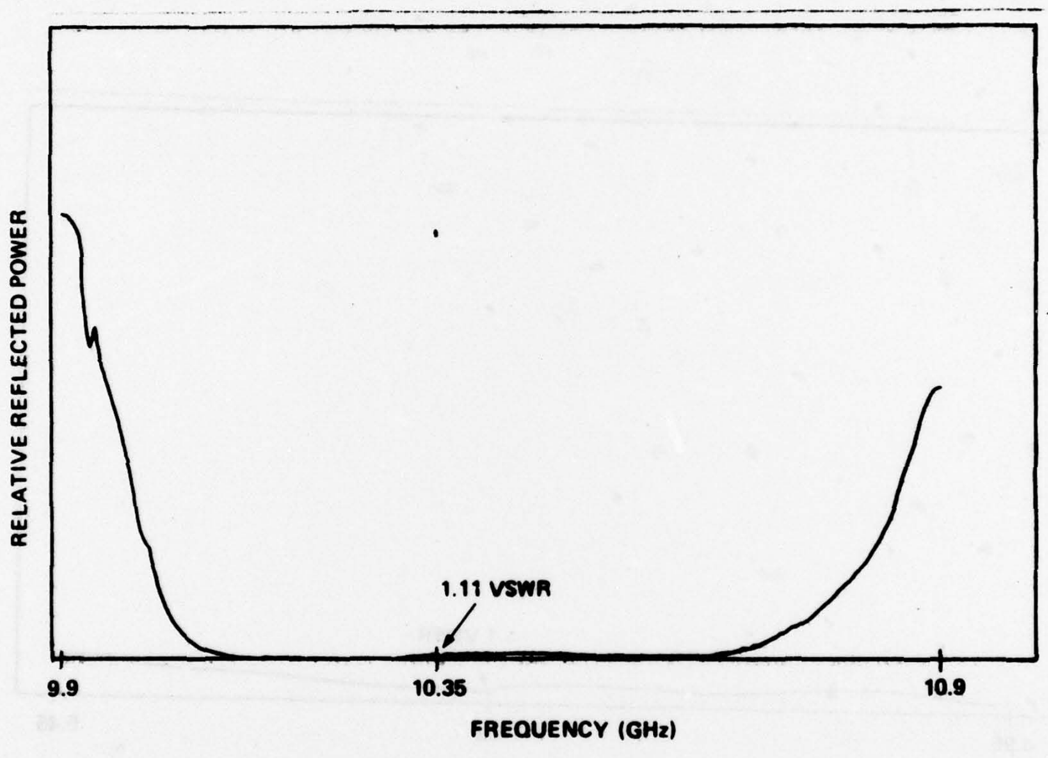

Figure 15. Reflected Power – Second Harmonic (TE_{01}) Circuit

V. CONCLUSIONS AND PLANS FOR THE NEXT PERIOD

The saturated power output measurements with the three-cavity gyroklystron amplifier resulted in a maximum measured efficiency in the range of 8 to 9% compared to a calculated value of 30%. The most likely reason for the low efficiency is the necessity to operate with reduced transverse energy on the beam to prevent spurious oscillations. Space-charge effects, which have not yet been included in the analysis, may also be contributing to reduced efficiency.

The noise figure and spectrum measurements for the gyroklystron amplifier indicate that these devices are reasonably high-fidelity amplifiers similar to linear-beam klystrons and TWTs. This conclusion must be tempered somewhat by the fact that the gain of the present device is limited to fairly low values like 6 to 10 dB.

During the next period, the experiments on the fundamental and second cyclotron harmonic gyro-TWTs will be completed. Design work will also be done on a device to test high cyclotron harmonic operation near X-band.

Additional work is needed on gyro-TWT analysis. Efficiency calculations have been started in cooperation with the Naval Research Laboratory on the fundamental and second cyclotron harmonic gyro-TWTs using existing theory [2,3]. The cooperation and assistance of Sprangle, Chiu, and Drobot at NRL is gratefully acknowledged in this work. During the next period at Varian, small-signal gain calculations will be performed, and work will be done on development of large-signal calculation codes. The possibilities of including circuit loss and space-charge effects will be investigated.

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